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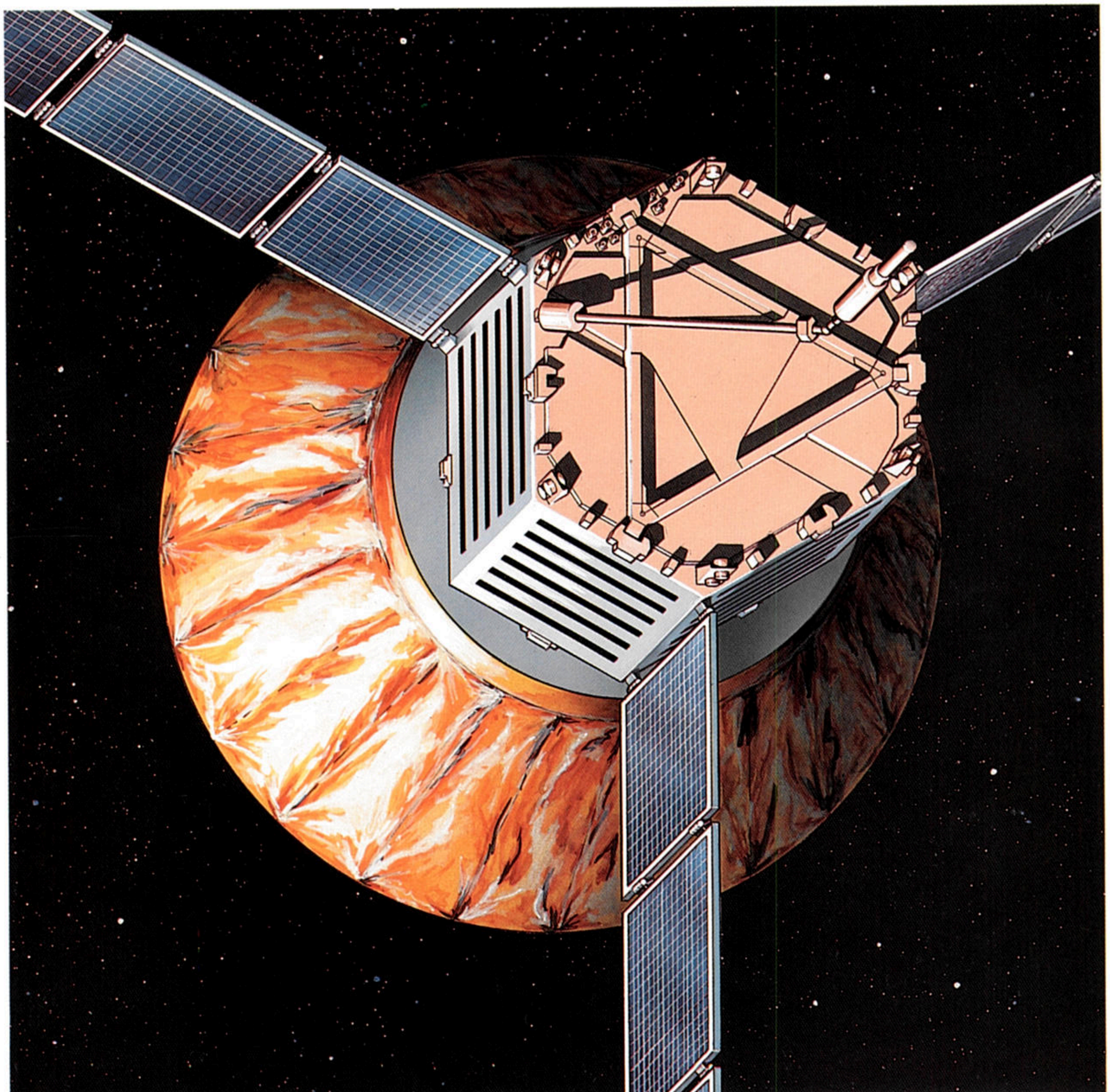

Cosmic Background Explorer *will tune in on the big bang in a search for clues to the origin of the universe.*

The Cosmic Background Explorer

NASA's cosmological satellite will observe a radiative relic of the big bang. The resulting wealth of data will be scoured for clues to the evolution of structure in the universe

by Samuel Gulkis, Philip M. Lubin, Stephan S. Meyer and Robert F. Silverberg

Late last year the National Aeronautics and Space Administration launched its first satellite dedicated to the study of phenomena related to the origins of the universe. The satellite, called the *Cosmic Background Explorer* (COBE), carries three complementary detectors that will make fundamental measurements of the celestial radiation. Part of that radiation is believed to have originated in processes that occurred at the very dawn of the universe. By measuring the remnant radiation at wavelengths from one micrometer to one centimeter across the entire sky, scientists hope to be able to solve many mysteries regarding the origin and evolution of the early universe.

The COBE data will be analyzed for clues to questions of the most fundamental nature: What were the conditions when the remnant radiation was emitted? How did the structures we see in the sky today develop? What was the cosmos like when the first luminous bodies formed? Can we see the diffuse radiation from a possible first generation of stars? Was there an era when masses of intergalactic dust absorbed much of the early starlight?

The cosmic radiation, created early in the evolution of the universe under drastically different conditions than those prevailing today, probably has several parts. Each part would have originated at a different stage in the evolution of the universe, and each would have been the result of different processes. The most well-established component is the cosmic microwave background (CMB) radiation, discovered nearly 26 years ago; the measurement of its properties has been an active area of research ever since. Another component is expected to be found in the infrared region of the spectrum. This cosmic infrared background (CIB), whose existence has not yet been confirmed, is the predicted consequence of the formation of the first objects from primordial material.

Unfortunately, these radiative relics of the early universe are weak and veiled by local astrophysical and terrestrial sources of radiation. The wavelengths of the various cosmic components may also overlap, thereby making the understanding of the diffuse celestial radiation a challenge. Nevertheless, the COBE instruments, with their full-sky coverage, high sensitivity to a wide range of wavelengths and freedom from interference from the earth's atmosphere, will constitute for astrophysicists an observatory of unprecedented sensitivity and scope. The interesting cosmic signals will then be separated from one another and from noncosmic radiation sources by a comprehensive analysis of the data.

The COBE mission has been profoundly shaped by the current understanding of the universe. The discovery of the CMB has led to wide acceptance of the hot big-bang theory, a remarkable synthesis of various observations that includes the expansion of the universe and its hydrogen-to-helium ratio, as well as the CMB itself. This theory asserts that the universe started from a primeval fireball, an extremely dense and hot state with a tiny volume, that has since expanded to its present scale. As it expanded, the matter and radiation cooled from temperatures so high that the behavior of the primordial "stuff" that existed in the first instant of the universe is beyond the predictive power of today's physics.

The cooling initiated events that led to the present universe. Neutrons and protons formed from their quark constituents. A few minutes later, nuclei of helium, deuterium and lithium coalesced from the protons and neutrons. Approximately 300,000 years after the big bang, as the universe cooled further, the nuclei combined with free electrons to form electrically neutral atoms. The initial formation of neutral atoms, referred to by cosmologists as the decoupling era, was of crucial importance to the development of stars and galaxies: it allowed the matter and radiation to evolve independently for the first time.

The radiation continued to cool as the universe expanded, so that today we observe it as the cosmic microwave background, whose properties closely resemble those of an ideal thermal source, called a blackbody, at a temperature of 2.7 kelvins. Even though it is now faint and cool, the CMB remains the dominant form of radiant energy in the universe today. Because the matter essentially stopped interacting with the radiation at the decoupling era, the present-day radiation gives us a "snapshot" of what the conditions were like when the universe was only about 300,000 years old.

After the era of decoupling, matter evolved unhindered by radiation pressure and, under the influence of gravi-

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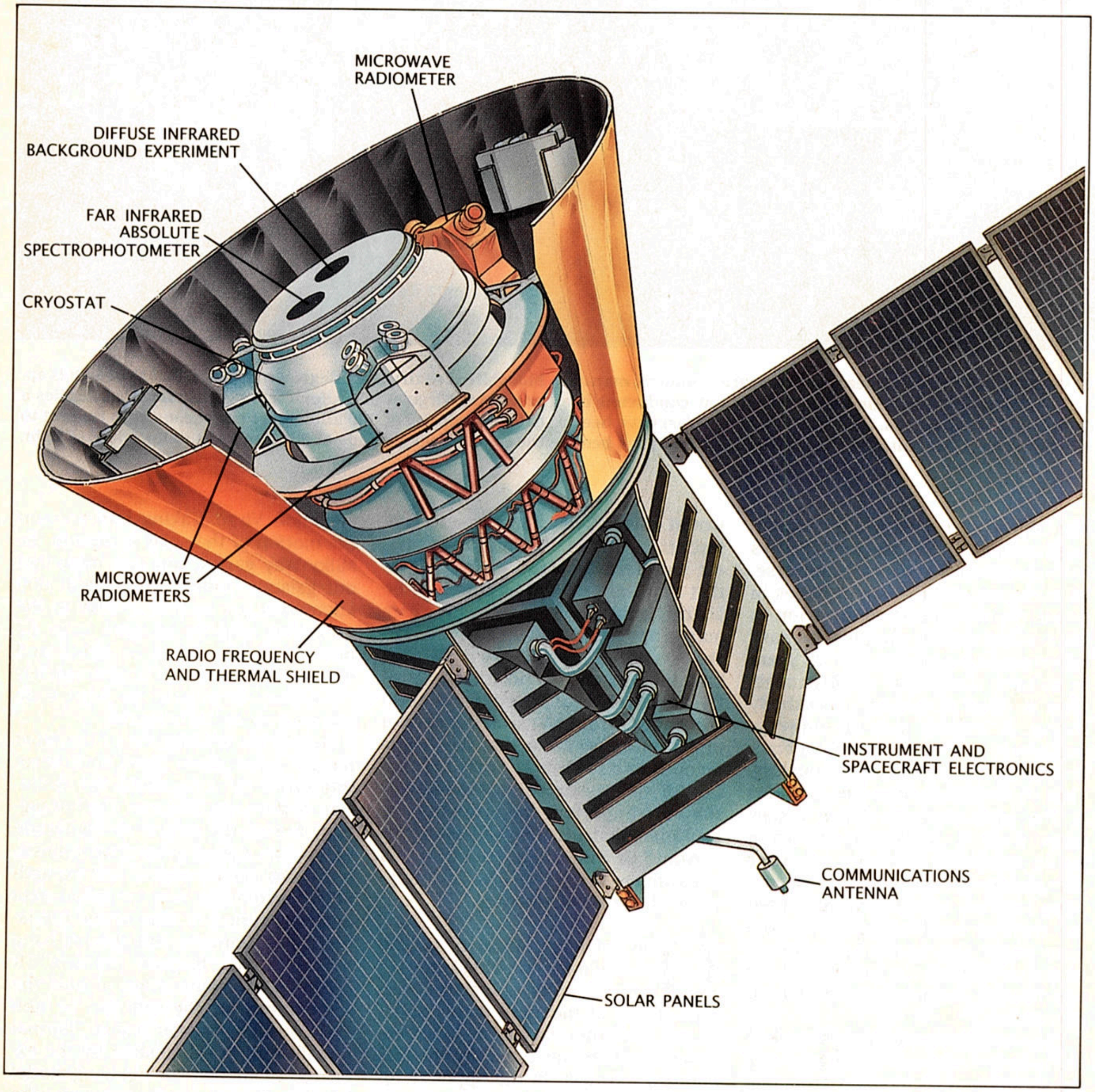
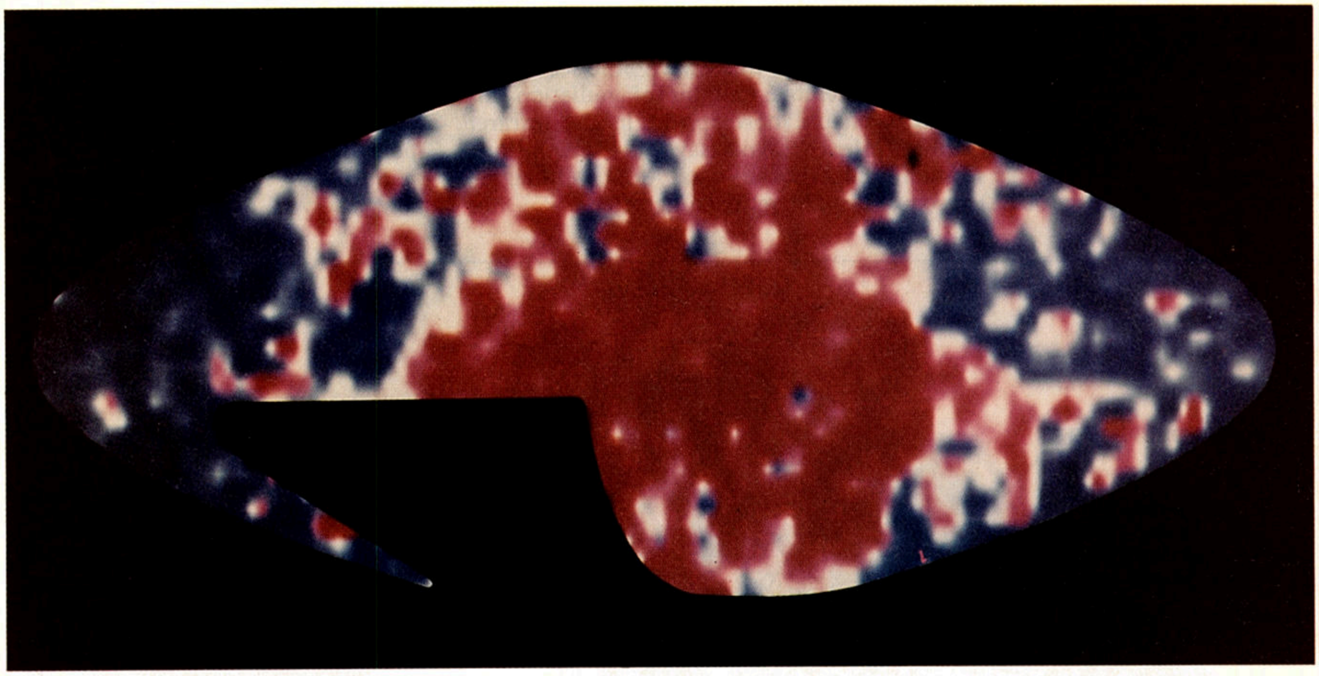
ty, collapsed into the celestial objects that we now see. Because significant amounts of elements heavier than helium have been observed in the oldest known stars, the material most likely was produced in an even earlier generation of stars that also formed during this collapse period. The energy from the gravitational collapse and the production of the first heavy elements must have produced a considerable amount of radiation that should now appear in the infrared. Hence, theory says, a cosmic infrared background must exist, although it has not yet been detected.

Although the scenario we have outlined is in accordance with existing measurements, it is hardly complete. Cosmologists do not know the conditions that prevailed between the initial moments of the universe and the formation of the most distant objects we now observe, a span of approximately



COSMIC BACKGROUND EXPLORER (COBE) scans the sky from an almost polar orbit near the earth's day-night terminator. A shield protects its three instruments from direct solar and terrestrial radiation. A year's supply of liquid helium, stored in the cryostat (a vacuum-insulated bottle), chills the far infrared absolute spectrophotometer (FIRAS) and the diffuse infrared background experiment (DIRBE) to improve sensitivity and reduce systematic errors. The FIRAS examines 1,000 celestial regions for evidence of energetic processes in the early universe. The DIRBE measures the absolute brightness of the sky for the vestige of the earliest starlight, a predicted but unverified phenomenon that might help explain the evolution of cosmic structure. A third set of observations is conducted by a set of three differential microwave radiometers (DMR's) deployed outside the cryostat. Each seeks to discover tiny spatial variations, or anisotropies, in the microwave intensity that might indicate whether matter was distributed unevenly at the time the cosmic microwave background radiation originated.



VAST DIPOLE in the sky appears in this nearly complete map of data collected by a balloon-borne experiment conducted by Lubin and his colleagues. The cooler regions (*blue*) have been redshifted by .1 percent, and the hotter region (*red*) has been blueshifted to the same degree, indicating that the earth is approaching Virgo at 300 kilometers per second. That implies a galactic velocity of 600 kilometers per second with respect to the cosmic background—about .2 percent of the speed of light.

one billion years. Still, two fundamental properties of the CMB provide clues to the conditions in the early universe: its spectrum and the way it varies in intensity with respect to direction in the sky—its angular variation. Because experiments during the past 25 years or so have shown that the CMB spectrum is close to that of a blackbody source, it is clear that the universe was nearly in a state of thermal equilibrium at the period of decoupling. This observation constrains theories of the early universe. Small departures from a blackbody spectrum would imply the existence of major energetic processes before the decoupling era that would have disrupted the thermal equilibrium. Such variations might also be the consequence of matter altering the radiation in the epochs that followed the period of decoupling.

The second notable characteristic of the cosmic microwave background, the variation of its intensity from one direction in the sky to another, provides clues that may help answer other questions. Such variations, called anisotropies, could be produced by a "lumpy" distribution of matter and energy at the time of decoupling or by relative motions between the different parts of the universe. Because large-scale structures such as galaxies would have taken a long time to coalesce if the initial distribution of matter had been uniform, theorists predict that the CMB will be found to be slightly anisotropic. Searches for CMB anisotropy that could be attributed to the "seeds" of present-day structures have been extensive and acutely sensitive, and yet results have been negative so far: on angular scales of several arc minutes, we know that the CMB is smooth to less than 20 parts per million. If one assumed that gravity is the only important force driving the evolution of structure on a large scale, it would be difficult to reconcile this smoothness in the CMB with the lumpiness of the visible matter.

One angular variation in the cosmic microwave background, believed to be associated with the velocity of the earth with respect to the radiation, has been detected. Along one direction in the sky, the CMB appears warmest; in the opposite direction it is coolest. The contrast is minute—only .1 percent warmer in the direction of the earth's motion and .1 percent cooler in the opposite direction. This angular variation, called a dipole distribution because it has two poles, implies that the earth has a velocity of about 300 kilometers per second as it moves toward the constellation Virgo. Taking into account the motion of the solar system in the Milky Way galaxy, one can infer that our galactic center is moving at 600 kilometers per second relative to the CMB. This velocity is quite large (.2 percent of the speed of light), and its meaning, although not completely clear, may be related to large-scale matter flow in the universe.

Such flows are but one of the most recent conceptions that have revolutionized thinking about the evolution of the early universe. The hot big-bang model, the central idea a decade ago, is still a good general hypothesis, but it has been modified and expanded to encompass new empirical data and new concepts. One of the fundamental difficulties with the big-bang model is the "horizon problem." It arises in the explanation of how the temperature of the CMB can be uniform on large angular scales. Thermal equilibrium is established by the exchange of energy. The big-bang model requires that the early expansion be so rapid that regions of the sky now separated by more than two degrees in angle could never have exchanged energy with each other, even if the energy traveled at the speed of light. Why then do all the parts of the sky now appear to have the same temperature? The probability of this having been a random occurrence is unimaginably small. A refinement of the model, a concept called the inflationary universe hypothesis, addresses the problem.

The inflationary picture explains the uniformity of temperature by postulating that the universe expanded at an enormous rate in its first few instants. In this model, the universe evolved from a small space that had been in thermal equilibrium prior to the time of inflation. Hence, the CMB is smooth because the CMB photons we see today issued from regions that were once in nearly perfect thermal equilibrium. What we see is therefore only a very small part of a region that had reached local equilibrium before the inflation.

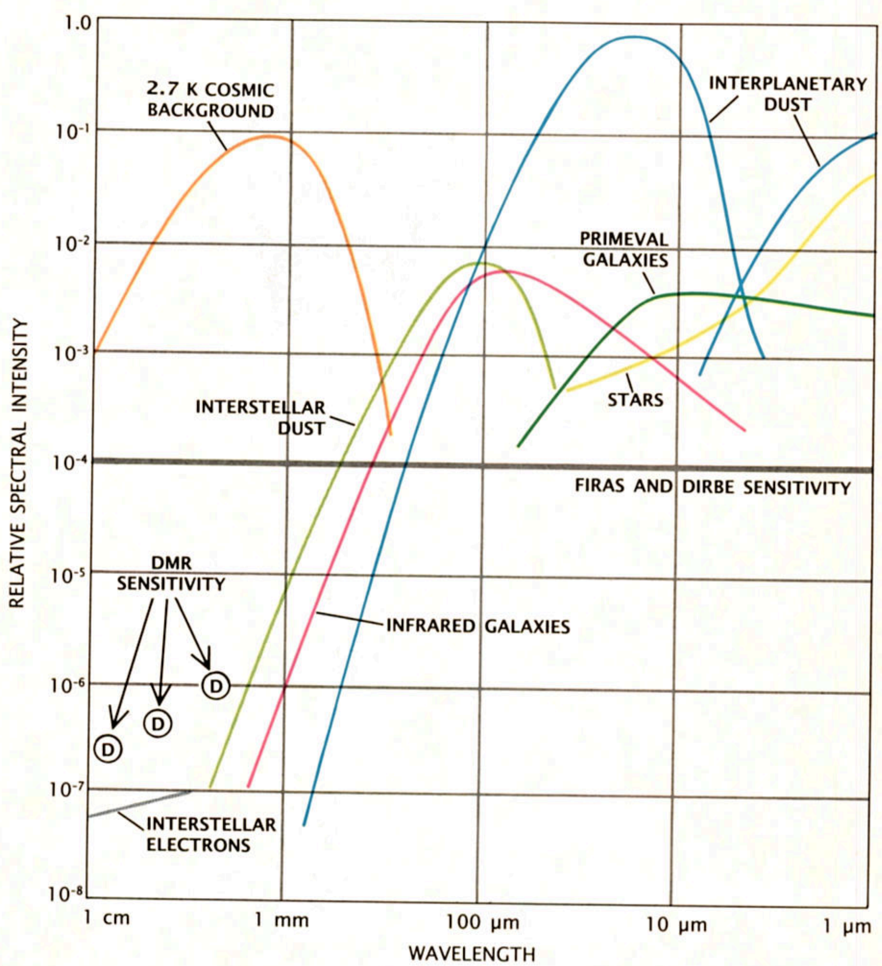
A second consequence of inflation is that the density of the universe is required to be a unique value, called the critical density. The critical density is far larger than the observed density, which implies that the universe contains much more matter than just the luminous stars and galaxies that we observe. The unseen mass could be in the form of cold, dark matter that emits no detectable radiation.

Inflation would also expand the quantum-mechanical density fluctuations that existed in the primordial material before the expansion began. This kind of fluctuation ought to have produced a characteristic form of anisotropy. Therefore, a third consequence of inflation is a prediction of how the CMB brightness should vary with angular separation across the sky. The discovery of fluctuations in the cosmic microwave background would be an important test of the validity of the inflationary model.

The extreme uniformity of matter in the early universe, inferred from the isotropy of the CMB, must be reconciled with the condensed structures we see in the present-day sky: galaxies, clusters of galaxies and superclusters. The dark-matter hypothesis has gained considerable favor in explaining this apparent dilemma. Incorporation of cold, dark matter into the big-bang picture has two effects. First, it permits the evolution of density perturbations to have started before the era of decoupling. This early formation of structure does not show up in the CMB, because the dark matter does not interact with the radiation. Second, the dark matter enhances the density in the universe and speeds the evolution of structure.

Studies of the distribution and redshifts of galaxies have led to surprising conclusions about the density and distribution of luminous matter. Enormous regions of space appear to be virtually free of any galaxies. These regions, called voids, are much larger than one would expect for randomly positioned matter that has clumped gravitationally. The theoretical challenge is to modify the hot big-bang picture so that one can reconcile the smooth distribution of the radiation at decoupling, represented by the cosmic microwave background, with the existence of large voids in the distribution of luminous matter. Examples of such modifications to the "standard hot big bang" cover a wide range of possibilities. Some cosmologists postulate that very small increases in the density cause very large increases in the tendency to form galaxies. Others propose that once cold, dark matter has clumped, it can decay, leading to explosions on a truly cosmic scale. Such cataclysms would account for the observed voids.

Measured distributions of the velocities of galaxies imply the existence of very large-scale structures in the cosmos. The velocity distribution measurements are exceedingly difficult and fraught with systematic bias, but several independent studies indicate that something unexpected is occurring. Widely separated galaxies seem to be moving in unison at velocities that would not be expected from a standard model of the evolution of the matter. It appears that our galaxy is on the edge of an enormous region of space that is moving as though gravitationally drawn toward an object dramatically named the Great Attractor. The surprisingly large velocity of the Milky Way relative to the CMB, as measured by the dipole variation, may be related to this motion. Both the voids and the large-scale motions constitute



EXPECTED BRIGHTNESS of the phenomena COBE will observe is graphed as a function of wavelength. Local sources of varying brightness across the sky are plotted at their expected minimum values; estimated sensitivities of the COBE experiments are also indicated. The 2.7-K cosmic microwave background dominates local sources over a large range of wavelengths. Radiation from the early galaxies should be nearly as intense as emissions from interplanetary dust at wavelengths near five micrometers.

experimental evidence that the big-bang model, even with the addition of cold, dark matter, has difficulty encompassing.

The question of how structure evolved from the uniformity of the early universe is also addressed by measuring the properties of the radiation emitted after the decoupling era. If matter had been as luminous in early epochs as it is today, a measurable cosmic infrared background should have been produced. There are several pieces of circumstantial evidence for the presence of such early luminosity. The oldest stars observed are known to contain significant amounts of elements heavier than helium; such elements can only be formed by nuclear fusion in the interior of stars. Because the heavy elements produced in stellar interiors do not become detectable until they are ejected into the interstellar medium by a star's death, the observed heavy elements in the oldest known stars must have been created in an earlier generation of stars.

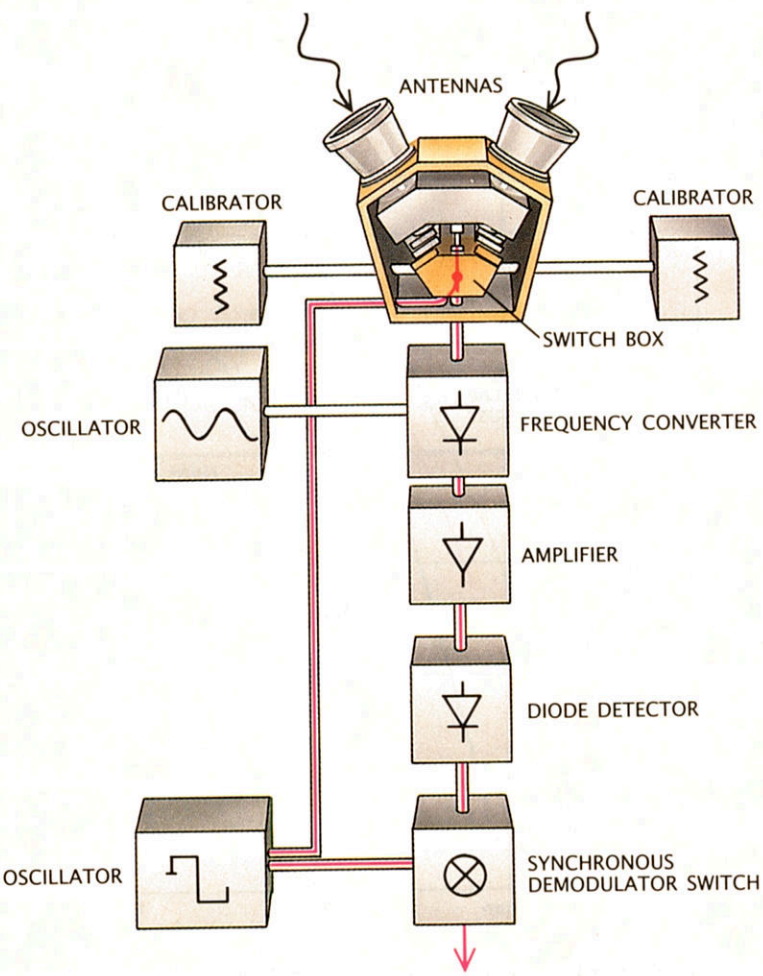
It is likely, therefore, that the oldest stars we see are from at least the second generation. Where is the light from the first generation of stars? Were these first stars smoothly distributed in space or clumped together to form the first galaxies? If they were clumped, the radiation might be found in highly redshifted protogalaxies (whose spectra have been shifted to longer wavelengths by their sources' rapid recession from the earth's frame of reference). Such protogalaxies would appear as extended dim patches in the sky. If the stars formed earlier than larger-scale structures did, then their light would appear as a uniform glow in all directions.

It is possible that, after the production of the heavy elements, some of the ejected material precipitated as dust. This dust would have absorbed the radiation from the first-generation stars. The dust would have heated up and reradiated the energy at longer wavelengths. The effect of such a process would be to make the energy from the early heavy-element-producing stars appear in the far infrared. If the density of the dust had been high enough, the angular structure of the infrared background would show noticeable variations.

It is evident that many new and exciting ideas about the formation and early development of the universe have been raised and that comprehensive and detailed observations of the cosmic background radiation are the key elements needed for sorting out these ideas. The faintness of the cosmic background relative to the astrophysical and terrestrial radiation conspire to make ground-, aircraft-, balloon- and rocket-based experiments extremely difficult.

Properly shielded from the sun and the earth and oriented to provide full-sky coverage, a satellite, however, can measure a broad range of wavelengths. The satellite can thus deepen understanding of the cosmic background as well as measure radiation from local sources.

This local radiation, rather than instrument sensitivity, sets the ultimate limits on the ability to measure the cosmic background. The foreground astrophysical sources include dust in our solar system, synchrotron radiation from electrons losing energy in galactic magnetic fields, thermal radiation from interstellar dust in our own galaxy and the integrated emission from the stars and external galaxies. Because the various sources can be distinguished according to their spatial and spectral characteristics, it is possible to separate the foreground sources from the cosmic backgrounds. Well-calibrated, multifrequency, full-sky maps are required to perform this separation.



DIFFERENTIAL MICROWAVE RADIOMETER measures the difference between the microwave radiation emitted from two points on the sky with two horn antennas that are alternately connected to a single receiver. Each horn's signal is compared with the signal from the other horn. This technique minimizes variations in receiver gain, variations that would reduce the sensitivity of systems using two receivers.

The COBE satellite was designed and built at NASA's Goddard Space Flight Center. The design combines a careful integration of instruments, spacecraft and orbit to reduce systematic errors, with instruments that cover a broad spectral range (near infrared to centimeter wavelengths) and can measure the background radiation across the sky.

Primary mission objectives are to search for angular anisotropies in the CMB, to measure its spectrum and to search for and measure the diffuse

CIB. Analysis of emissions from the foreground astrophysical sources is also an objective of the mission. Such knowledge is intrinsically important to understanding the origin and evolution of both our solar system and galaxy. Furthermore, the cosmic backgrounds cannot be determined without this knowledge.

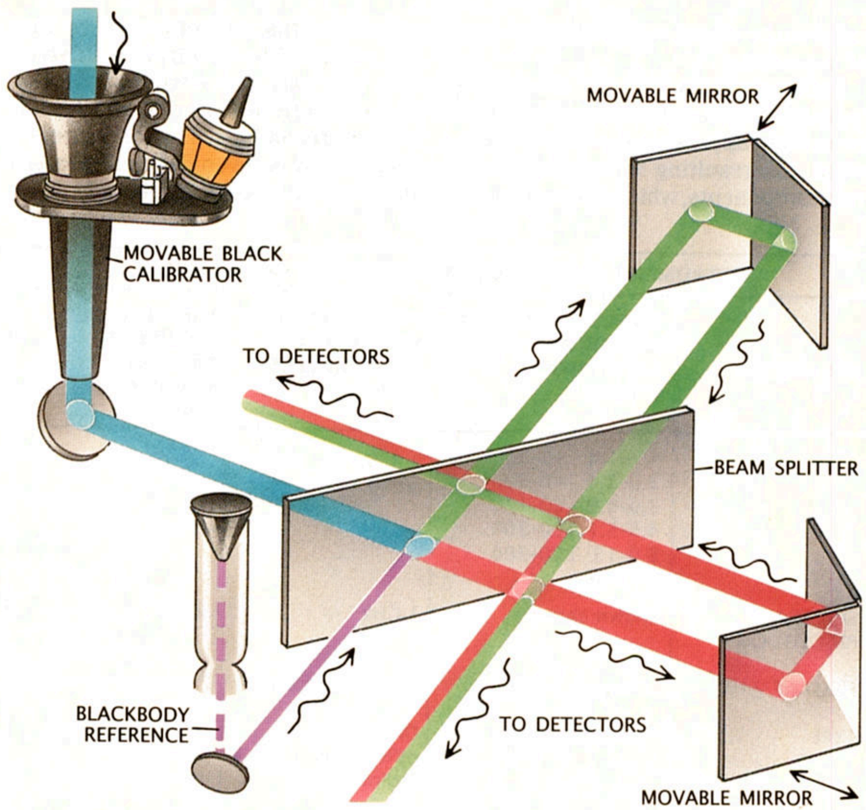
COBE carries three complementary detectors: a set of differential microwave radiometers, a polarizing Michelson interferometer and an infrared filter photometer. Each measures a different aspect of the cosmic background radiation. The instruments have each been designed to minimize systematic errors and to provide the sensitivity needed to measure the cosmic backgrounds.

The differential microwave radiometers (DMR's) will measure the large-scale anisotropy in the CMB to better than one part in 100,000, an extremely small variation. Data from this instrument will be used to search for the seeds of the present large-scale structures, anisotropic expansion or rotation of the universe, gravity waves, large-scale flows of matter and cosmic strings. Theory predicts that such strings—which can be considered as massive, one-dimensional objects—will have formed just after the big bang. If they did, they may have provided a framework on which large-scale structures could grow.

The radiometers achieve their high sensitivity by rapidly switching between two nearly identical horn antennas, each aimed at an angle of 30 degrees with respect to the spacecraft's axis of spin. Measured power differences are then converted to temperature differences in the sky by comparison with references supplied by onboard sources and measurements of the moon. There are three separate receiver boxes, one for each of the three wavelengths. The specific wavelengths were chosen to optimize the capability to distinguish between local galactic and dust emissions and the cosmic microwave background.

To provide higher sensitivity, critical components of the two shorter wavelength radiometers are passively cooled by radiation to about 140 K, while the longest wavelength radiometers operate near room temperature. The cooled radiometers can detect a temperature difference of about .025 K in a one-second measurement. The room-temperature radiometers are less sensitive by a factor of approximately two. The sensitivity of the data from each DMR receiver after one year of observation will be about 100 microkelvins (.0001 K) per seven-degree field of view on the sky. This level of sensitivity is about seven times better than that of the three-millimeter map shown on page 134.

By combining these points, the DMR will be able to measure temperature variations on large angular scales as small as 10 microkelvins. Such variations are 300 times smaller than the amplitude of the confirmed dipole variation mentioned earlier. Even the dipole temperature difference caused by the motion of the earth around the sun with respect to the CMB will appear as a large signal relative to the instrument's noise.



FAR INFRARED ABSOLUTE SPECTROPHOTOMETER compares the spectrum of radiation from the sky at wavelengths from 100 micrometers to one centimeter with that from an internal blackbody, or perfect source of radiation; differences between the two would constitute evidence that the universe underwent energetic processes near the time of decoupling. A trumpet-shaped horn funnels light into a beam splitter, which directs two parts (*red and green lines*) along paths whose lengths are varied by movable mirrors. The components are then recombined at the beam splitter to form an interference pattern that reveals the signal's spectral nature.

The Michelson interferometric spectrometer, or far infrared absolute spectrophotometer (FIRAS), will measure the spectrum of the background radiation from one centimeter to 100 micrometers for each of 1,000 parts of the sky. Deviations from the spectrum of a blackbody will be measured to within one part in 1,000. A deviation would indicate the presence of very energetic sources in the early universe. Scattering of cosmic background photons by hot electrons produces a well-known change in the blackbody spectrum. This perturbation would indicate the presence of a hot, ionized gas produced by energy injection well after decoupling. Such heating could have been produced by the formation of stars or galaxies.

The FIRAS, like the DMR, is a differential instrument. It compares the spectral power received from the sky with an internal reference source that has a controllable temperature and calibrated emission properties. The high accuracy of the FIRAS instrument is attributable to a movable calibration source that may be placed in the entrance of the input horn. The spectrum emitted by the calibrator is within .01 percent of a blackbody. The temperature of the calibrator is adjusted to match the flux from the sky as closely as possible. Any remaining spectral differences between the blackbody and the sky can then be measured at a high degree of sensitivity.

Radiation from the sky enters the instrument through a trumpet-shaped cone that suppresses the off-axis radiation. The resulting beam is split into two components, which traverse paths whose lengths are controlled by mobile mirrors. The spectrum is inferred from the way the waves of the two beams interfere with one another after they recombine. The instrument's field of view is seven degrees, directed along the spacecraft's spin axis.

INSTRUMENT PARAMETERS AND SCIENCE TEAM MEMBERS

PARAMETER	DIFFUSE INFRARED MICROWAVE EXPERIMENT (DIRBE)	DIFFERENTIAL MICROWAVE RADIOMETERS (DMR's)	FAR INFRARED ABSOLUTE SPECTRO-PHOTOMETER (FIRAS)
WAVELENGTH	1.1–1.4 15–30 2.0–2.4 40–80 3.0–4.0 80–120 4.5–5.1 120–200 8.0–15 200–300 (in μm)	3.3, 5.7 and 9.6 mm	.10–10 mm
SPECTRAL RESOLUTION	Shown above	1 GHz	.2 cm^{-1}
FIELD OF VIEW	.7 degree square	7 degrees diameter	7 degrees diameter
TYPE	Filter photometer	Dicke-switched differential radiometers	Fourier-transform polarizing interferometer
FLUX COLLECTOR	Off-axis Gregorian telescope	Corrugated horns separated by 60 degrees	Smooth flared horn
SENSITIVITY (IN FIELD OF VIEW)	10^{-13} W cm^{-2}	.0001 K (3.3 and 5.7 mm), .00025 K (9.6 mm) (after 1 year)	< 10^{-13} W cm^{-2} (.5–5 mm)
LINE OF SIGHT	30 degrees off spin axis	30 degrees off spin axis	Spin axis
DETECTOR	Photovoltaics for < 5.1, photoconductors for 8–120, bolometers for 120–300	Diode mixer	Bolometers (4)
CALIBRATION	Internal reference and celestial sources	Noise diode and moon	Blackbody temperature controlled to within .001 K
DATA RATE (BITS/SEC)	1,713	216	1,330

COBE Science Team Members

Goddard Space Flight Center:	Charles L. Bennett, Nancy W. Boggess, Eli Dwek, Michael G. Hauser (principal investigator for DIRBE instrument), Thomas Kelsall, John C. Mather (COBE project scientist and principal investigator for FIRAS instrument), S. Harvey Moseley, Jr., Richard A. Shafer, Robert F. Silverberg
Massachusetts Institute of Technology:	Edward S. Cheng, Stephan S. Meyer, Rainer Weiss (chair of the COBE science team)
Jet Propulsion Laboratory:	Samuel Gulkis, Michael A. Janssen
University of California, Santa Barbara:	Philip M. Lubin
General Research Corporation:	Thomas L. Murdock
University of California, Berkeley:	George F. Smoot (principal investigator for DMR instrument)
Princeton University:	David T. Wilkinson
University of California, Los Angeles:	Edward L. Wright

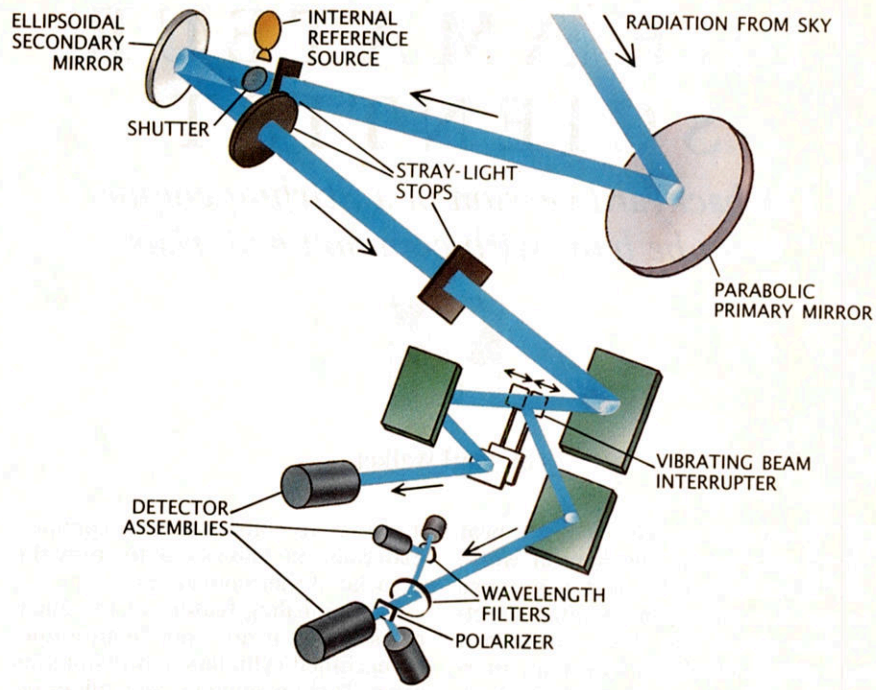
The third detector, the diffuse infrared background experiment (DIRBE), will measure the absolute brightness of the sky at wavelengths ranging between one and 300 micrometers. This instrument will perform the most sensitive search yet undertaken for the diffuse infrared light from the early universe—light from the first generation of protogalaxies, galaxies and stars. The spectral range of the radiation would indicate the nature of its originating processes. DIRBE will also make important measurements of the emissions from foreground sources such as interstellar and interplanetary dust, galactic starlight, infrared galaxies, quasars and galactic clusters.

DIRBE's optics have been designed and built to eliminate all stray light from off-axis sources as well as radiation from the spacecraft and the instrument itself. A system of light baffles, radiation stops and extremely clean, highly polished mirrors ensures that the radiation contributed by extraneous sources will be small. The instrument will be able to measure a small residual background radiation with a sensitivity of about 1 percent of the local astrophysical foreground emission. The basic instrument design is that of an unobscured off-axis Gregorian telescope with a primary mirror diameter of 20 centimeters; the field of view is .7 by .7 degree. The telescope is aimed 30 degrees away from the satellite spin axis so that the rotation varies the angle between the DIRBE line of sight and the sun. A device resembling a tuning fork interrupts the sky beam 32 times per second to compare the incoming radiation from each point on the sky with the near-zero light level of a cold reference surface within the instrument. Detectors at 10 different wavelengths observe the same field simultaneously to cover the spectrum from one to 300 micrometers.

The DIRBE will also measure the polarization of the incoming light in the three shortest-wavelength bands. This information will enable it to characterize the sunlight that is scattered from the interplanetary dust. The four middle bands are dominated by the thermal emission of the interplanetary dust, but the receivers for those bands are sensitive enough to detect the diffuse emission from an early generation of stars. The channels measuring the longest wavelengths will search for radiation that may have been reradiated by intergalactic dust produced from this early generation of stars. DIRBE has enough spectral coverage and sensitivity to separate the emissions of planetary and galactic dust from the interesting cosmic sources. The questions of whether radiation was emitted from an early generation of stars or larger structures and whether such radiation might have been absorbed and reemitted by intergalactic dust are uniquely suited to an analysis based on DIRBE's observations.

Among the satellite's other components are a large cryostat (a vacuum-insulated tank containing liquid helium), a deployable radiation shield, a power system and an attitude-control system. The shield protects the sensitive instruments and the cryostat from solar and terrestrial thermal radiation and from radio-frequency interference. The DIRBE and FIRAS are mounted inside the cryostat to maintain them at a temperature of less than 2 K; this arrangement minimizes radiation from the instruments themselves and permits the use of sensitive detectors. The cryostat contains enough superfluid helium to chill the instruments for the nominal mission lifetime of about one year, the time needed to achieve the required sensitivity and full-sky coverage. The DMR is mounted outside the cryostat, but it, too, is protected by the radiation shield. Solar-cell panels supply electric power to the satellite except during short eclipse periods, which occur during only part of the year. At such times batteries will be used.

The entire satellite, comparable in size and weight to a large automobile, was lifted into orbit by a Delta vehicle, launched from the Western Space and Missile Center in California. The COBE orbit allows the three kinds of scientific instruments to scan the entire sky while keeping them in a stable thermal environment with minimal interference from the sun and the earth. It is a nearly polar, circular orbit at an altitude of 900 kilometers, arranged to remain near the earth's day-night terminator (the border of the sunlit portion of the globe). The attitude-control system keeps the instrument's view directions aligned about 90 degrees from the sun and 180 degrees from the earth. The entire spacecraft rotates at .8 revolution per minute, producing a scan pattern that reduces systematic errors in the DMR and giving DIRBE a range of solar-illumination angles from which to view reflections from the interplanetary dust. Because the brightness of the interplanetary dust depends strongly on the ecliptic latitude and the sun's illumination angle, the emission from these particles will be easy to recognize and thus easy to remove from the data. The rotation also ensures that the sun heats the satellite uniformly, reducing temperature gradients within the satellite.



DIFFUSE INFRARED BACKGROUND EXPERIMENT searches for the radiation from the earliest generation of stars, scouring it for clues to the ancient distribution of matter from which today's cosmic structures evolved. Light is collected by a primary mirror; stray radiation is eliminated by light stops and baffles. The beam is divided into 10 components, which pass through different wavelength filters. The bands are analyzed for their intensity; three are analyzed for their polarization properties.

The data gathered by COBE's instruments will constitute a set of fundamental information of unprecedented scope and accuracy. The information will be analyzed and plotted as maps of the whole sky that span four orders of magnitude in wavelength. Two sets of results will be published and delivered to the National Space Science Data Center within three years of the launch. The first is a set of maps, calibrated and corrected for all known instrumental and spacecraft effects. The second set will show the microwave and infrared backgrounds that remain after the effects of the local astrophysical sources are removed.

The data from COBE will answer many questions about the early universe. Some of these have been asked for centuries while others have arisen more recently, as a result of new evidence. We can anticipate that cosmology will make a leap forward because of COBE discoveries.

In the long run, however, it is the comprehensive data set itself that will be COBE's greatest contribution. That set will be vastly more valuable than the sum of its parts. The uniformity of the analysis, the ability of each instrument to confirm the results of the others and the sheer completeness of the information will lead to a level of reliability unachievable in a mission of lesser proportion. Future investigations of the early universe and large-scale structure, in whatever direction the field progresses, will depend on COBE's legacy.

FURTHER READING

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